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Probing the Standard Model via rare pion and muon decays

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The PIBETA collaboration has used a non-magnetic pure CsI calorimeter operating at the Paul Scherrer Institute to collect the world's largest sample of rare pion and muon decays. We have extracted the absolute $\pi^+ \to \pi^0 e^+ \nu$ decay branching ratio with the 0.55 % total uncertainty. The $\pi^+ \to e^+ \nu\gamma$ data set was used to extract weak axial and vector form factors F_A and F_V, yielding a significant improvement in the precision of F_A and F_V. The $\mu^+ \to e^+ \nu\nu\gamma$ distributions were well described with the two-parameter ($\rho_{\rm SM}, \bar{\eta} = 0$) solution. These results bring major improvements in accuracy over the current Particle Data Group listings and agree well with the predictions of the Standard Model.

1. INTRODUCTION

The PIBETA experiment at the Paul Scherrer Institute (PSI) is a collaboration of seven institutions that collected the world largest sample of rare pion and muon decays during the 1999-2001 and 2004 beam periods [1].

The PIBETA detector system is based on a large acceptance 240-module pure CsI electromagnetic shower calorimeter. The detector includes with an active degrader AD, a segmented active target AT, a 20-bar cylindrical plastic scintillator veto PV for particle identification, a pair of tracking cylindrical multi-wire proportional chambers MWPC1/2 and an active cosmic veto shield [2].

A schematic drawing of the detector is shown in Fig. 1. The incident 114 MeV/c π^+ beam with a minimal e^+/μ^+ contamination was tagged with a thin forward beam counter BC, slowed down in the degrader and ultimately stopped in a tight $\sigma_{x,y} \simeq 9$ mm spot in the active target. The 1999-2001 runs, optimized for the pion beta decay measurement, used beam fluxes of up to 1 MHz. Beam intensities of 50-200 π^+/s were used in the 2004 for optimal acquisition of radiative decay events.

The recorded data, comprising $2.2 \cdot 10^{13}$ π^+ stops, were obtained by a dedicated two-arm high-threshold trigger as well as 11 physics

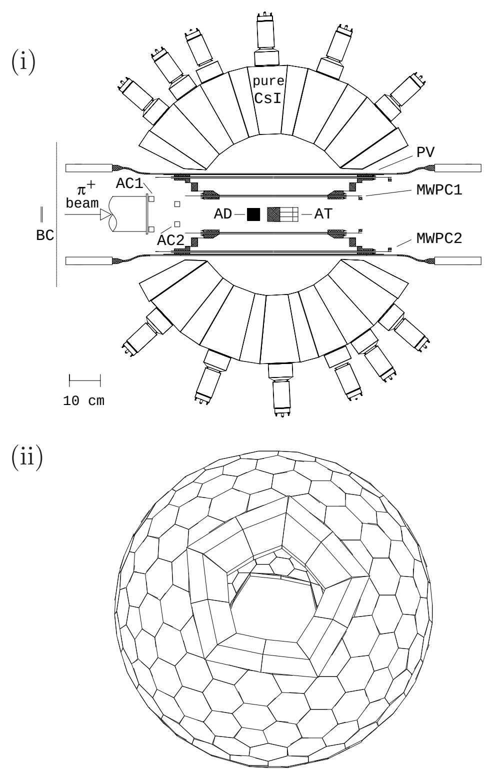

Figure 1. Pibeta detector: (i) cross-sectional view showing the major detector sub-systems, and (ii) 240-module pure CsI calorimeter geometry.

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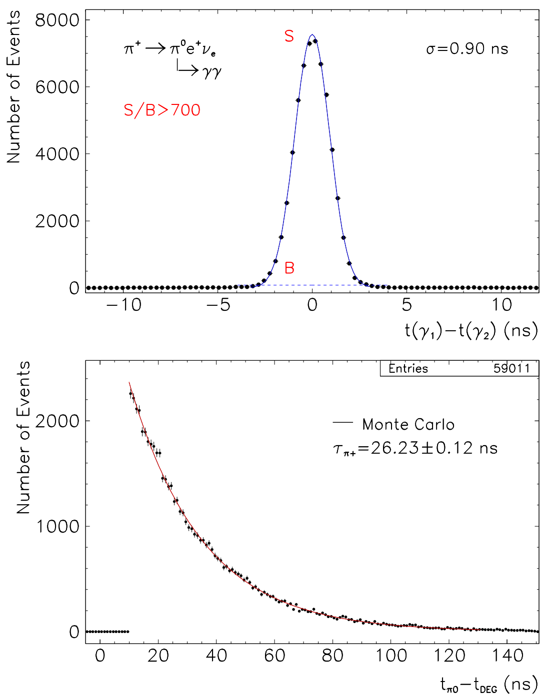

Figure 2. Representative pion beta decay experimental spectra: (i) Signal-to-background ratio, and (ii) measured life time for the $\pi\beta$ events.

and calibration triggers, some of which were prescaled.

2. PION BETA DECAY

Pion beta decay ($\pi^+ \to \pi^0 e^+ \nu$) rate offers one of the most precise means of testing the conserved vector current hypothesis (CVC) [3] and studying the weak u-d quark mixing [4]. The Standard Model (SM) description of the $\pi\beta$ decay is theoretically unambiguous within a 0.1 % uncertainty [5,6], but a small $\sim 1 \cdot 10^{-8}$ branching ratio poses significant experimental chalenges. The 3.9 % uncertainty of the previous most precise measurement, made using the π^0 spectrometer at LAMPF [7], was not accurate enough to test the full extent of radiative corrections which stand at $\sim 3\,\%$ [8].

The fast analog hardware triggers were designed to accept nearly all non-prompt $\pi\beta$ and and a sample of prescaled $\pi^+ \to e^+\nu$ events with individual shower energy exceeding the Michel endpoint (high threshold $\simeq$ 52 MeV).

The data analysis provided clean distributions of 64,047 $\pi\beta$ decay events which agreed very well with energy, angular and timing spectra predicted by the GEANT3 Monte Carlo detector simulations. The cosmic muon, prompt, radiative pion and accidental backgrounds were determined to be $< 1/700$ of the $\pi\beta$ signal, Fig. 2.

We have chosen to normalize the $\pi\beta$ yield to the yield of $\pi^+ \to e^+\nu$ events whose branching ratio is known with 0.33 % uncertainty experimentally [9,10] and $\leq$ 0.05 % accuracy theoretically [11,12]. Using the PDG [13] recommended value of $R^{\rm exp}_{\pi\to e\nu} = 1.230(4)\cdot 10^{-4}$, we find the pion beta branching ratio [14]:

$$R^{\rm exp}_{\pi\beta} = [1.036 \pm 0.004({\rm stat}) \pm 0.005({\rm syst})]\cdot 10^{-8}. \tag{1}$$

When normalizing to the theoretical value $R^{\rm the}_{\pi\to e\nu} = 1.2353 \cdot 10^{-4}$[11] we obtain:

$$R^{\rm exp}_{\pi\beta} = [1.040 \pm 0.004({\rm stat}) \pm 0.005({\rm syst})]\cdot 10^{-8}. \tag{2}$$

Our result for $R^{\rm exp}_{\pi\beta}$ is in excellent agreement with the prediction of the SM:

$$R^{\rm SM}_{\pi\beta} = (1.038 - 1.041) \cdot 10^{-8}, \tag{3}$$

and stands as the most accurate confirmation of the CVC in a meson to date.

3. RADIATIVE PION DECAY

The radiative pion decay $\pi^+ \to e^+\nu\gamma$ contributes to the background of the $\pi\beta$ process, but is also interesting in its own right. Precise measurement of its absolute branching ratio provides a consistency check of the data analysis, and new values of the weak axial and vector π^+ form factors, together with limits on the non-$(V-A)$ contributions to Standard Model Lagrangian [15].

Table 1
The fitted and theoretical values of the absolute branching ratios for three experimentally accessible regions of the phase space in the radiative pion decay.

$E_{e+}^{\min}/E_{\gamma}^{\min}/\theta_{e\gamma}^{\min}$ MeV/MeV/deg	$R_{\mathrm{RPD}}^{\mathrm{exp}}$ $(\times 10^{-8})$	$R_{\mathrm{RPD}}^{\mathrm{the}}$ $(\times 10^{-8})$
50/50/40°	2.655(58)	2.6410(5)
10/50/40°	14.59(26)	14.492(5)
50/10/40°	37.95(60)	37.90(3)

The fitted $R_{\mathrm{RPD}}^{\mathrm{exp}}$ values are based on 2004 data set.

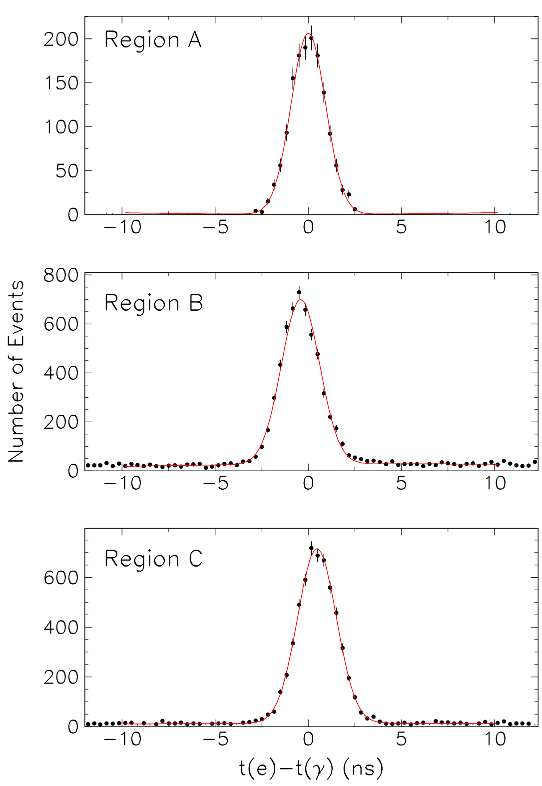

Figure 3. Signal-to-background ratio for the radiative pion decay candidate events in three regions of the measured phase space (see text for details).

We have recorded the radiative pion events in three overlapping phase space regions: (1) region A, restricted to e^+-γ coincident pairs for which both measured energies in the calorimeter were $E^C_{e^+,\gamma} > 55.6\,\mathrm{MeV}$, and for which the opening angle was $\theta^C_{e^+\gamma} > 40.0°$ (3.0 k events in 2004), (2) region B, with measured positron calorimeter energy $E^C_{e^+} > 20.0\,\mathrm{MeV}$, the photon energy $E^C_{\gamma} > 55.6\,\mathrm{MeV}$ and the relative angle $\theta^C_{e^+\gamma} > 40.0°$ (6.9 k events), and (3) region C, with measured photon calorimeter energy $E^C_{\gamma} > 20.0\,\mathrm{MeV}$, the positron energy $E^C_{e^+} > 55.6\,\mathrm{MeV}$ and the relative angle $\theta^C_{e^+\gamma} > 40.0°$ (9.1 k events).

The signal-to-background timing spectra for all three regions are shown in Fig. 3.

In order to account properly for the detector energy-angle resolutions, the experimental partial branching ratios were calculated for larger regions limited by the physical "thrown" kinematic variables as shown in Table 1. The integrated radiative corrections of $-1.0\,\%$ (region A), $-1.4\,\%$ (B), and $-3.3\,\%$ (C) have been added to the theoretical $R_{\mathrm{RPD}}^{\mathrm{the}}$ [16].

The three-dimensional least chi-square (χ^2) fit resulted in a new experimental value of the weak vector form factor:

$$F_V(q^2 = 0) = 0.0262 \pm 0.0015, \qquad (4)$$

and the improved value of the weak axial form factor:

$$F_A(q^2 = 0) = 0.0118 \pm 0.0003, \qquad (5)$$

where q^2 stands for the momentum transfer to the lepton pair. The third fit parameter was the

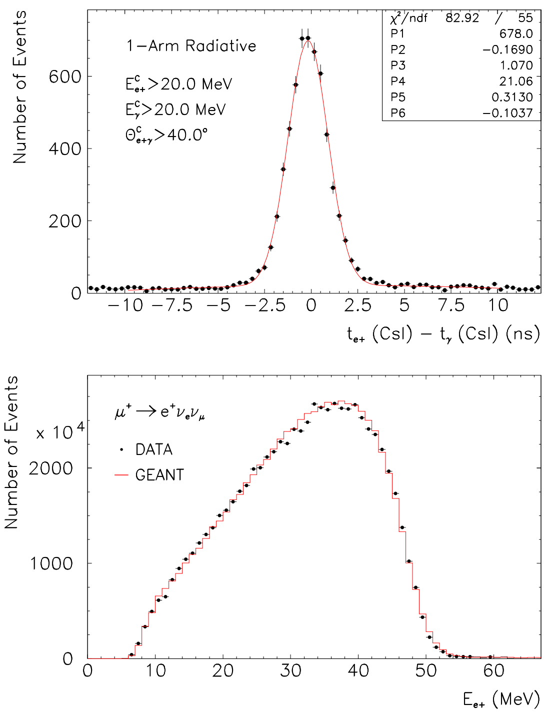

Figure 4. Signal-to-background ratio for the radiative muon decay candidate events (top) and energy spectrum of the normalizing Michel decay (bottom).

first measurement of the form factor's momentum dependence:

$$F(q^2) = F(0)\,[1 + (0.241 \pm 0.093)] \cdot q^2. \quad (6)$$

The above-quoted fit had χ^2 per degree of freedom of 0.6. The addition of a hypothetical tensor interaction term to the decay amplitude (see [17–19]) results in the upper limit of $|F_T(0)| \leq 5.1 \cdot 10^{-4}$ at the 90 % confidence limit [20]. This limit is more than an order of magnitude smaller than the ISTRA collaboration re-analysis result reported by Poblaguev [21].

4. RADIATIVE MUON DECAY

The radiative muon decay $\mu^+ \to e^+\nu\nu\gamma$ measurement provides another critical consistency check of overall analysis. In the Standard Model this process is parameterized via Michel parameters all of which, save $\bar{\eta}$, can be determined from the ordinary muon decay [22]. A non-zero value of $\bar{\eta}$ would imply the non-$(V-A)$ structure of the electroweak interaction.

The most recent direct measurement of $\bar{\eta}$ can be interpreted as an upper limit of 0.141 (at 90 % CL) [23].

Our two-dimensional Michel parameter fit $(\rho, \bar{\eta})$ of the $4.2 \cdot 10^5$ radiative muon events collected in 2004 (Fig. 4) corresponds to the upper limit $\bar{\eta} \leq 0.060$ and simultaneously yields the SM value $\rho = 0.751 \pm 0.010$ [24]. The details are summarized in Table 2.

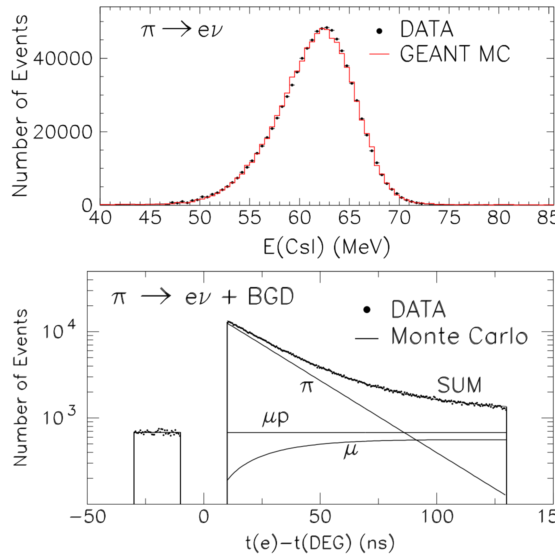

Figure 5. The energy line shape of the rare $\pi^+ \to e^+\nu$ events in CsI calorimeter (top) and timing distribution fit to $\pi^+ \to e^+\nu$ candidate events (bottom).

5. RARE $\pi \to e\nu$ DECAY

We have proposed to perform a new precise measurement of the $\pi^+ \to e^+\nu$ branching ratio at PSI using a suitably upgraded PIBETA detector system. The experiment has been approved with high priority in 2006. The measurement is motivated by the fact that at present accuracy of that branching ratio lags behind the theoretical

Table 2
The optimal values of parameters ρ and $\bar{\eta}$ in the radiative muon decay: two-dimensional fit (the first line) and the fit with ρ fixed at the Standard Model value (the second line).

$\bar{\eta}$	ρ
$-0.081 \pm 0.054(\text{stat.}) \pm 0.034(\text{syst.})$	0.751 ± 0.010
$-0.084 \pm 0.050(\text{stat.}) \pm 0.034(\text{syst.})$	0.75 (fixed at SM)

The fitted $R^{\text{exp}}_{\text{RMD}}$ values are based on 2004 data set.

precision by an order of magnitude.

We will build on our past experience in exploiting the $\pi \to e\nu$ decay for normalizing purposes (Fig. 5). We plan to rebuild the target region of the detector and develop the new digitizing detector for the beam counters. The proposed accuracy of the new measurement is $\sim 5 \cdot 10^{-4}$ or lower.

6. CONCLUSION

We have reported new and improved absolute branching ratios for the following rare decays: (1) $\pi^+ \to \pi^0 e^+\nu$, (2) $\pi^+ \to e^+\nu\gamma$, and (3) $\mu^+ \to e^+\nu\nu\gamma$. The yields of $\pi^+ \to e^+\nu$ and $\mu^+ \to e^+\nu\nu$ decays that were used for normalization are also internally consistent when compared to the total measured number of decaying π^+'s and μ^+'s [25].

Our results confirm the CVC hypothesis in the π^+ system at 0.55 % level, rule out the tensor contribution in the radiative π^+ decay with the form factor $|F_T| \geq 5.1 \cdot 10^{-4}$ (90 % CL), and set the new 90 % CL limit on the parameter $\bar{\eta} \leq 0.060$ in the radiative μ^+ decay.

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